

CLAIMS

What is claimed is:

1. A carrier tracking circuit, comprising:

a first phase adjustment circuit having a phase adjustment input, an input sample input,
5 and an output;

a delay element having an input coupled to the output of the first phase adjustment circuit and having an output;

a second phase adjustment circuit having a component input coupled to the output of the delay element, a phase adjustment input, and an output; and

10 a phase correction circuit having an input coupled to the output of the second phase adjustment circuit and a first output coupled to the phase adjustment input of the first phase adjustment circuit, the phase correction circuit including a double phase correction circuit having an input coupled to the first output and having a second output coupled to the phase adjustment input of the second phase adjustment circuit.

15 2. The carrier tracking circuit of claim 1 further comprising a feed forward phase correction circuit having a first control input adapted to receive a feed forward scale factor signal and a second control input coupled to the first output of the phase correction circuit, and having a component input coupled to the output of the second phase adjustment circuit.

20 3. The carrier tracking circuit of claim 1 wherein the phase correction circuit further comprises:

a phase estimation circuit having an input coupled to the output of the second phase adjustment circuit and having an output;

25 a loop filter having an input coupled to the output of the phase estimation circuit and having an output; and

a delay circuit having an input coupled to the output of the loop filter and an output coupled to the phase adjustment input of the first phase adjustment circuit.

4. The carrier tracking circuit of claim 1 wherein the delay element comprises an FFT element.

5. The carrier tracking circuit of claim 1 wherein each of the first and second phase adjustment circuits comprises a numerically-controlled oscillator.

6. The carrier tracking circuit of claim 1 wherein the first phase adjustment circuit further comprises a step phase adjustment circuit adapted to receive a phase step factor signal.

10 7. A carrier tracking circuit, comprising:
a first phase adjustment circuit adapted to receive input samples and operable to adjust a phase value of each input sample responsive to a first phase adjustment signal to thereby generate a corresponding phase-adjusted input sample, with groups of the input samples corresponding to sequentially received symbols;
15 a delay element coupled to the first phase adjustment circuit and operable to generate a group of output components responsive to a group of the phase-adjusted input samples corresponding to a particular symbol;
a second phase adjustment circuit coupled to the delay component to receive the output components, the second phase adjustment circuit operable to adjust a phase value of each
20 output component responsive to a second phase adjustment signal to thereby generate phase-adjusted output components corresponding to a particular symbol; and
a phase correction circuit coupled to the first and second phase adjustment circuits,
the phase correction circuit operable to generate the first phase adjustment signal having a value that is a function of the values of the phase-adjusted output components for a particular symbol, and operable to delay application of the phase adjustment signal to the first
25 phase adjustment circuit for approximately a first delay time at which a first input sample of a subsequent symbol is applied to the first phase adjustment circuit, and
the phase correction circuit further operable to generate the second phase adjustment signal having a value that is equal to the value the first phase adjustment signal for a

second delay time and that is thereafter equal to a new value of the first phase adjustment signal associated with a subsequent symbol minus an initial value of the first phase adjustment signal associated with the prior symbol, the second delay time being equal to approximately the time between when the initial value of the first phase adjustment signal is generated and the time when the output components for a subsequent symbol that have been phase adjusted using that initial value are output from the delay element.

8. The carrier tracking circuit of claim 7 wherein the phase correction circuit further comprises a feed forward phase correction circuit coupled to the output of the second phase adjustment circuit, the feed forward phase correction circuit operable to adjust the phase values of the phase adjusted output components for a particular symbol using the first phase adjustment signal generated from the phase adjusted output components of that symbol.

9. The carrier tracking circuit of claim 8 wherein the feed forward phase correction circuit generates a feed forward offset phase by multiplying the first phase adjustment signal by a feed forward scale factor, and subtracts the feed forward offset phase from the phase values of the phase adjusted output components.

10. The carrier tracking circuit of claim 9 wherein the feed forward scale factor is less than one.

11. The carrier tracking circuit of claim 10 wherein the feed forward phase correction circuit comprises:

a summation circuit that receives the phase adjusted output components on a first input and that receives the feed forward offset phase on a second input, the summation circuit operable to subtract the offset phase from the phase values of each output component to provide on an output feed forward phase adjusted output components; and

a multiplier having a first input coupled to receive the first phase adjustment signal, a second input coupled to receive the feed forward scale factor, and an output coupled to the

second input of the summation circuit, the multiplier operable to multiply the first phase adjustment signal times the feed forward scale factor to provide the feed forward offset phase to the summation circuit.

5 12. The carrier tracking circuit of claim 7 wherein the first phase adjustment circuit further comprises a step phase compensation circuit adapted to receive a phase step factor signal and being operable to generate a step phase value in response to the first phase adjustment signal and the phase step factor signal, and wherein the first phase adjustment circuit is operable to subtract the step phase value plus a value of the first phase adjustment
10 signal from the first input sample of each symbol.

 13. The carrier tracking circuit of claim 12 wherein the first phase adjustment circuit is further operable to incrementally increase the value subtracted from each subsequent input sample in a given symbol by the value of the first phase adjustment signal.

15

 14. The carrier tracking circuit of claim 7 wherein the first phase adjustment circuit further comprises a numerically controlled oscillator and wherein the second phase adjustment circuit comprises a numerically-controlled oscillator.

20 15. The carrier tracking circuit of claim 7 wherein the delay element comprises a fast Fourier transform (FFT) element and wherein a group of the phase-corrected input samples correspond to a time domain sample of an OFDM symbol, the FFT element being operable to generate as output components a group of frequency components for the OFDM symbol in response to the group of phase-corrected input samples. (16.) An OFDM receiver, comprising:

25

 a radio frequency receiver circuit;
 an analog-to-digital converter coupled to the radio frequency receiver circuit;
 a serial-to-parallel converter coupled to the analog-to-digital converter;
 an FFT circuit coupled to the serial-to-parallel converter;
 a parallel-to-serial converter coupled to the output of the FFT circuit;

a symbol demodulation circuit; and

a carrier tracking circuit coupled to the analog-to-digital converter and to the parallel-to-serial converter, the carrier tracking circuit including,

5 a first phase adjustment circuit coupled to receive input samples from the analog-to-digital converter and operable to adjust a phase value of each input sample responsive to a first phase adjustment signal to thereby generate a corresponding phase-adjusted input sample, with groups of the input samples corresponding to sequentially received OFDM symbols;

10 a second phase adjustment circuit coupled to the FFT circuit to receive output components from the FFT, the second phase adjustment circuit operable to adjust a phase value of each output component responsive to a second phase adjustment signal to thereby generate phase-adjusted output components corresponding to a particular OFDM symbol; and

a phase correction circuit coupled to the first and second phase adjustment circuits,

15 the phase correction circuit operable to generate the first phase adjustment signal having a value that is a function of the values of the phase-adjusted output components for a particular OFDM symbol, and operable to delay application of the phase adjustment signal to the first phase adjustment circuit for approximately a first delay time at which a first input sample of a subsequent OFDM symbol is applied to the first phase
20 adjustment circuit, and

the phase correction circuit further operable to generate the second phase adjustment signal having a value that is equal to the value the first phase adjustment signal for a second delay time and that is thereafter equal to a new value of the first phase adjustment signal associated with a subsequent OFDM symbol minus an initial value of the first phase adjustment
25 signal associated with the prior OFDM symbol, the second delay time being equal to approximately the time between when the initial value of the first phase adjustment signal is generated and the time when the output components for a subsequent OFDM symbol that have been phase adjusted using that initial value are output from the FFT.

17. The OFDM receiver of claim 16 wherein the phase correction circuit further comprises a feed forward phase correction circuit coupled to the output of the second phase adjustment circuit, the feed forward phase correction circuit operable to adjust the phase values of the phase adjusted output components for a particular OFDM symbol using the first phase adjustment signal generated from the phase adjusted output components of that OFDM symbol.

18. The OFDM receiver of claim 16 wherein the first phase adjustment circuit is further operable to incrementally increase the value subtracted from each subsequent input sample in a given OFDM symbol by the value of the first phase adjustment signal.

19. The OFDM receiver of claim 16 wherein the first and second phase adjustment circuits each include numerically controlled oscillators.

20. The OFDM receiver of claim 16 wherein the symbol demodulation circuit comprises a QAM demapping circuit.

21. An OFDM communications system, comprising:
an OFDM transmitter operable to communicate a modulated OFDM signal over a wireless communications channel; and
an OFDM receiver including,
a radio frequency receiver circuit adapted to receive the modulated OFDM signal;
an analog-to-digital converter coupled to the radio frequency receiver circuit;
a serial-to-parallel converter coupled to the analog-to-digital converter;
an FFT circuit coupled to the serial-to-parallel converter;
a parallel-to-serial converter coupled to the output of the FFT circuit;
a symbol demodulation circuit; and
a carrier tracking circuit coupled to the analog-to-digital converter and to the parallel-to-serial converter, the carrier tracking circuit including,

a first phase adjustment circuit coupled to receive input samples from the analog-to-digital converter and operable to adjust a phase value of each input sample responsive to a first phase adjustment signal to thereby generate a corresponding phase-adjusted input sample, with groups of the input samples corresponding to sequentially received
5 OFDM symbols;

a second phase adjustment circuit coupled to the FFT circuit to receive output components from the FFT, the second phase adjustment circuit operable to adjust a phase value of each output component responsive to a second phase adjustment signal to thereby generate phase-adjusted output components corresponding to a particular OFDM
10 symbol; and

a phase correction circuit coupled to the first and second phase adjustment circuits,

the phase correction circuit operable to generate the first phase adjustment signal having a value that is a function of the values of the phase-adjusted output components for a particular OFDM symbol, and operable to delay application of the phase
15 adjustment signal to the first phase adjustment circuit for approximately a first delay time at which a first input sample of a subsequent OFDM symbol is applied to the first phase adjustment circuit, and

the phase correction circuit further operable to generate the
20 second phase adjustment signal having a value that is equal to the value the first phase adjustment signal for a second delay time and that is thereafter equal to a new value of the first phase adjustment signal associated with a subsequent OFDM symbol minus an initial value of the first phase adjustment signal associated with the prior OFDM symbol, the second delay time being equal to approximately the time between when the initial value of the first phase
25 adjustment signal is generated and the time when the output components for a subsequent OFDM symbol that have been phase adjusted using that initial value are output from the FFT.

22. The OFDM communications system of claim 21 wherein the phase correction circuit further comprises a feed forward phase correction circuit coupled to the output of the

second phase adjustment circuit, the feed forward phase correction circuit operable to adjust the phase values of the phase adjusted output components for a particular OFDM symbol using the first phase adjustment signal generated from the phase adjusted output components of that OFDM symbol.

5

23. The OFDM communications system of claim 21 wherein the first phase adjustment circuit is further operable to incrementally increase the value subtracted from each subsequent input sample in a given OFDM symbol by the value of the first phase adjustment signal.

10

24. The OFDM communications system of claim 21 wherein the first and second phase adjustment circuits each include numerically controlled oscillators.

15

25. The OFDM communications system of claim 21 wherein the symbol demodulation circuit comprises a QAM demapping circuit.

26. A method of correcting for frequency offset in a communications system that communicates data symbols, the method comprising:

20 generating a first group of frequency components that correspond to a data symbol by applying an FFT algorithm to a group of time domain input samples that correspond to the symbol;

calculating a phase adjustment value from the group of frequency components;

25 adjusting the phase values of subsequent groups of time domain input samples corresponding to subsequent symbols in using the calculated phase adjustment value for a prior symbol, the phase values of the subsequent time domain input samples being adjusted prior to applying the FFT algorithm to these input samples;

adjusting the phase values of the groups of frequency components generated by the FFT algorithm for a given symbol using the phase adjustment value calculated from the frequency components of a prior symbol; and

when a given symbol has the phase values of the corresponding time domain input samples adjusted using the phase adjustment value calculated from a particular prior symbol, compensating for this adjustment to the time domain input samples when adjusting the phase values of the group of frequency components corresponding to this given symbol.

5

27. The method of claim 26 further comprising adjusting the phase values of the group of frequency components for a given symbol using the phase adjustment value calculated from that group of frequency components

10

28. The method of claim 26,
wherein each group of time domain input samples includes $r(1)$ - $r(N)$ input samples; and
wherein adjusting the phase values of subsequent groups of time domain input samples includes,

15

subtracting a phase increment from the phase values for each of the time domain input samples $r(1)$ - $r(N)$ in a group, the phase increment linearly increasing from the first input sample $r(1)$ to the last input sample $r(N)$.

20

29. The method of claim 28 wherein subtracting a phase increment further comprises subtracting a step phase value from the first input sample $r(1)$, the step phase value being determined as function of the how each phase adjustment value is calculated.

25

30. The method of claim 29 wherein each phase adjustment value is calculated to represent the average phase error corresponding approximately to the phase error of the $r(N/2)$ input sample, and the step phase value is equal to $N/2$ plus an offset value plus an incremental value to be linearly applied to the input samples having their phase values adjusted.

31. The method of claim 26 wherein each of the symbols comprises an OFDM symbol.

32. The method of claim 26 wherein compensating for the adjustment to the time domain input samples when a given symbol has the phase values of the corresponding time domain input samples adjusted using the phase adjustment values calculated from a particular prior symbol comprises subtracting the phase adjustment value generated from the particular prior symbol from a current phase adjustment value and using the difference to adjust the phase values of the frequency components corresponding to the particular symbol when these components are output from the FFT.

33. The method of claim 26 wherein each symbol comprises an OFDM symbol.

34. A method of correcting for frequency offset in an OFDM communications system that communicates OFDM symbols, each OFDM symbol including a plurality of corresponding time domain input samples and a plurality of corresponding frequency components generated by applying a frequency analysis algorithm to the time domain input samples, each time domain input sample and each frequency component having an associated phase and magnitude, the method comprising:

calculating a phase adjustment value from the frequency components of each OFDM symbol;

adjusting the phases of the time domain input samples of at least one prior OFDM symbol using the calculated phase adjustment value for a prior OFDM symbol prior to applying the input samples to the frequency analysis algorithm;

adjusting the phases of the frequency components of at least one prior OFDM symbol using the calculate phase adjustment value for a prior OFDM symbol; and

adjusting the phases of the frequency components of a given OFDM symbol using the calculated phase adjustment value for that OFDM symbol.

35. The method of claim 34 wherein the frequency analysis algorithm comprises an FFT algorithm.

36. The method of claim 34 wherein adjusting the phases of the frequency components of a given OFDM symbol using the calculated phase adjustment value for that OFDM symbol comprises:

5 multiplying the calculated phase adjustment value by a feed forward scale factor to generate a feed forward offset value; and

subtracting the feed forward offset value from each of the frequency components of the given OFDM symbol.

37. The method of claim 34 wherein adjusting the phases of the time domain input
10 samples of a given OFDM symbol comprises subtracting a linearly increasing phase increment from each of the input samples.

38. The method of claim 37 wherein the phase of the first sample of the OFDM
15 symbol is further adjusted by subtracting a step phase value.

39. The method of claim 38 wherein the step phase value is calculated using one half the number of input samples for each OFDM symbol plus an offset value determined by the number of cyclic prefix samples in the OFDM symbol.

20 40. The method of claim 34 further comprising compensating for double phase correction of both the time domain input samples and the frequency components of a given OFDM symbol by the same calculated phase adjustment values.

25 41. The method of claim 40 wherein this compensation comprises subtracting the phase adjustment value generated from the particular prior symbol from a current phase adjustment value and using the difference to adjust the phases of the frequency components corresponding to the particular symbol when these components are output from the frequency analysis algorithm.